

Mass Balance of Biomass Conversion by Gasification

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Participant:

Signature

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Signature

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Abstract

Mass Balance of a Biomass Conversion Process. MICHELE L. BUZEK (University of Colorado, Boulder, CO, 80309) STEVEN PHILLIPS (National Renewable Energy Laboratory, Golden, CO 80401).

The primary goal of this assignment was to perform an overall mass balance of the biomass conversion process of the Thermochemical Process Development Unit (TCPDU) at National Renewable Energy Laboratory (NREL). Before performing the mass balance, information on each of the instruments was researched. The theoretical error of each instrument was determined from the manufacturer's specifications. The total uncertainty of each measurement was calculated using the Root Sum of the Squares (RSS) method. Each of the instruments was tested and an error analysis was performed to determine the actual error associated with each instrument. The experimental results were then compared to the theoretical values. Once the errors were determined, an Excel spreadsheet was set up to calculate the mass balance. A graph was generated to show a visual representation of the mass balance with the error limits. Using Visual Basic programming language, a macro was created to automate this process. The program is designed to import the run-time data for a user-specified date from the data server and generate the mass balance spreadsheet and graph. This program can be utilized to generate a mass balance using data files from previous plant runs, as well as a mass balance for current plant runs where the program is refreshed approximately every twenty minutes, generating a near real-time mass balance.

Research Category: Engineering

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Introduction

Biomass Conversion in the TCPDU

Biomass conversion is a thermochemical process that converts organic materials into energy. A thermochemical reaction occurs when a chemical change is induced solely by the presence of heat (Feik and Phillips, 2002). The TCPDU is dedicated to the research of plant-based biomass conversion processes achieved either by gasification or pyrolysis. The research of this assignment is based on biomass conversion of corn fiber by gasification, which involves heating the corn fiber to a high temperature while minimizing the amount of oxygen present. Limiting the amount of oxygen prevents the combustion of the biomass, only allowing it to gasify.

A diagram of the TCPDU is shown in Figure 1. Biomass is dumped into the hopper and a controller monitors the mass feed rate to an 8-inch fluidized-bed reactor. Fluidization is achieved by injecting superheated steam into the reactor through a distributor plate. Electrical heaters mounted to the vessel wall heat it to temperatures between 450°C and 700°C. The high temperatures cause the solid feed to volatilize and the conversion process begins. The vapors are then sent to a thermal cracker where the temperature is further increased to 800° and the conversion process is completed forming a mixture of various gases and solid carbon matrix particles, commonly known as char. The char is removed from the system by a series of cyclones. The gas is sent to a scrubber where some of the gases are condensed by cooling water. The condensed liquid is cooled again by a heat exchanger and is directed to a settling tank. Any char that was not previously removed from the system will collect at the bottom of the settling tank. Once the liquid

in the settling tank reaches a certain level, the excess is drawn off, taken out of the system and distributed to an overflow barrel. The remaining liquid in the settling tank is filtered to remove any contaminants and the water is recycled back to the scrubber to be used for cooling. The gases that did not condense in the scrubber are cooled by a chilled cyclone to remove entrained droplets of liquid. These liquids, if any, are sent to the settling tank. The remaining gaseous mixture is filtered by coalescing filters, which remove any aerosols that may be present. The final product is syngas, which is a mixture of varying amounts of hydrogen (H₂), carbon dioxide (CO₂), carbon monoxide (CO) and methane (CH₄). The syngas is then sent to an engine where it is burned to produce power (Feik and Phillips, 2002).

A General Mass Balance

A mass balance is an essential part of chemical engineering. An accurate and complete mass balance will confirm the validity of a process, making it possible to perform necessary analyses, including plant design, plant performance and cost analysis. A general mass balance accounts for the overall mass entering, exiting and accumulating in a system. The balance is performed using the following equation

$$\sum m_{\text{in}} - \sum m_{\text{out}} - \sum m_{\text{accumulated}} \equiv 0$$

This states that the sum of the masses flowing into a system, minus the sum of the masses flowing out of the system, minus the sum of the mass being accumulated within the system must be equal to zero. The first step in performing a mass balance is defining the system and identifying its boundaries. Once the system is defined, all the mass terms should be identified. The TCPDU has three inlet terms: biomass, superheated steam, and

sometimes air; three outlet terms: char, aqueous waste, and syngas; and one measured accumulation term: the contents of the settling tank. Finally, after all the terms are identified, you just “plug-n-chug”.

Accounting for the Errors

While a mass balance may be a trivial task to perform on paper, performing an accurate mass balance on a running system requires a little more work than just addition and subtraction of the masses involved. For a complete mass balance, the uncertainty of the measurements must be determined and taken into account in the calculations. Performing a mass balance based on incorrect or inaccurate data can potentially be more problematic than not performing a mass balance at all.

A mass balance can be a valuable tool for trouble-shooting. All the mass that flows through and accumulates within a system must be accounted. If the masses do not balance, it may be an indication of a problem. Because it might be difficult to assess the situation if the errors are great or the error limits are unknown, it must be reiterated that the measurements must be evaluated and analyzed to determine these limits. Because all data will contain some degree of uncertainty, an analyst should determine what amounts of error are acceptable and possible solutions for reducing any errors that are unacceptable should be considered.

Collecting the Data and Performing the Calculations

Data acquisition software is used to record the various measurements involved in running the biomass conversion plant. A number of data files are generated and each of the files contain a log of various measurements. For a general material balance, only the mass measurements and the mass flow rate measurements are necessary. Because the existing files are so large and nearly impossible to interpret in a reasonable amount of time, a new data file that contains only the measurements required for completing the mass balance was created. The data file is copied into an Excel spreadsheet. Another spreadsheet is then created and the data is organized in a user-friendly format. The necessary calculations are performed to determine the mass contributions for each time range. The masses are then totaled and the corresponding error limits are calculated using the RSS method. Finally a visual representation of the mass balance for the day is shown, and the error limits are indicated on the graph.

Automating the Mass Balance Process

A number of subroutines, also called macros, were developed using Visual Basic programming language to enhance the Excel application. These macros perform each of the steps necessary to complete the mass balance. A program that incorporates several macros was developed to automate the overall mass balance process. The end result is an automated program that imports the necessary data file into Excel, creates a spreadsheet detailing all the calculations and produces a real-time visual representation of the material balance. The program is designed to run on a near real-time basis for current plant runs, refreshing the data approximately every twenty minutes. The program can also be utilized to perform or view a mass balance for a prior day's plant run.

Materials and Methods

The mass flow rates of the gases entering and leaving the system are measured using four Coriolis mass flow meters. Each of the mass flow meters used in the TCPDU consist of a Micro Motion Elite Sensor (Model CMF025) and one of two Micro Motion Field Mount Transmitters (Models IFT9701 and RFT9739). The mass flow rate of the gas entering the system is measured by a flow meter that uses an RFT9739 transmitter. Two flow meters arranged in a parallel configuration are used to measure the mass flow rates of the gases exiting the system. Both of these flow meters use an IFT9701 transmitter.

The biomass entering the system is contained in a hopper, which sets upon three K-Tron KSFT II Load Cells. The biomass then enters a K-Tron KMLT50 Loss-in-Weight Feeder and is fed to the system. A K-Tron K10S Controller monitors the feed rate.

A bench scale weighing system measures the mass of solids and liquids exiting the system. Each weighing system is set up in the same configuration, with the only variance being the model of the bench scale(s) used. Each scale is connected to a Mettler-Toledo Weighing Terminal (Model ID1), which is then connected to a Mettler-Toledo Analog Output Module (Model 9325), which finally connects to a 12-bit analog-to-digital converter.

The char that is removed from the system is weighed using a 150-kilogram Mettler-Toledo Bench Scale (Model KCC150). The capacity is scaled down to 30 kilograms. The water that enters the system for cooling purposes is either recycled to the system or distributed into a drum. The clean water that recycles through the system is not accounted for in the mass balance. Although the water is a part of the system, it does not cross the boundaries of the system and therefore is not considered in the mass balance. The contaminated water that passes through the system and is distributed into the drum is weighed on a two-scale configuration of KCC150 scales, giving the total mass capacity of 300 kilograms. The solid and liquid contents of the settling tank are weighed using a 1500-kilogram Mettler-Toledo Scale (Model KD1500).

The manufacturers' specifications for each instrument are documented in Tables 1A to 3D. Only the specifications relevant to this project are shown. However, the contact information for obtaining the complete specification sheet is given for each manufacturer. The theoretical error for each instrument was determined using the values given in the corresponding specifications. Each of the measurements necessary for the mass balance calculations is obtained by using multiple instruments. Because there is an uncertainty associated with each instrument, each of these uncertainties must be taken into account when determining the total error associated with the measurement. The combined error of the measurement was calculated using the RSS method. The actual errors of each instrument were determined by performing various tests on the instruments. When possible, proper adjustments were made to the instrument to increase its accuracy. The

experimental results of the error analysis were then compared to the theoretical values that were calculated.

Results

The results of the error analyses are shown in Figures 2A to 5. The figures show percent error as a function of either mass or mass rate. For each of the figures, the solid lines indicate the theoretical values calculated from the specification sheets and the dashed lines indicate the experimental results. The results for the bench scale systems are grouped as Figures 2A to 2C. The data points are indicated by square data-markers. The results for the Coriolis flow meters are shown as Figure 3. The data points are indicated by circle data-markers. The solid data-markers indicate the experimental error of the flow meter measuring the gas flow into the system. The empty data-markers indicate the combined error of the flow meters measuring the gas flow out of the system. The results for the biomass feeder system are shown in Figure 4. The data points are indicated by triangle data-markers. This figure has a maximum and minimum theoretical error. This is because the error associated with the feeder is dependant on the characteristics of the feed. The maximum error trend is indicated by a solid data-marker and the minimum error trend is indicated by an empty data-marker.

Figures 2A to 2C show the comparison of the errors associated with the three different bench scale systems in the TCPDU. At a first glance, the theoretical trends appear to be

the same for each bench scale system. At a second glance, it should be noticed that the range of the x-axis is different for each system. Each x-axis ranges from zero to the scale's full capacity. Since each bench scale system has an identical configuration, with the exception of the bench scale, the scale's capacity is the only differing factor in determining the error. Hence the similar theoretical trend when ranged from zero to full capacity. As indicated in each of these three figures, the experimental results yielded errors less than the theoretical values. In Figure 2C, the experimental values only cover a small range compared to the theoretical values. This is because only a small number of weights, totaling 97 kilograms were available for testing. It was assumed that the error would continue to decrease after the second peak as it did in Figures 2A and 2B.

The theoretical error of the Coriolis flow meters shown in Figure 3 is infinitesimal. Theoretically, it makes the smallest contribution to the total error. However, as determined by error analysis, the trend shows that this error is much greater than determined theoretically and is a significant factor in calculating the total error.

Figures 4 show the errors associated with the biomass feeder system. The theoretical error range varies from 10.003% to 10.05% based on the characteristics of the feed. For the sake of simplicity, the theoretical error will be considered to be 10%. The figure shows two separate experimental trends, one for peanut pellets and one for corn fiber. The data points for peanut pellets are indicated by solid data-markers and the data points for corn fiber are indicated by empty data-markers. The error, when feeding corn fiber, is less than both the theoretical error and the error when feeding peanut pellets. The error,

when feeding peanut pellets, is greater than the theoretical error at lower feed rates and is less than the theoretical error at higher feed rates.

Figure 4 shows a comparison of all the errors associated with calculating the mass balance. As in the previous figures, solid lines represent the theoretical trends and dashed lines indicate the experimental trends. The various instruments are distinguishable by the different data-markers.

Discussion and Conclusion

As seen in Figure 5, the feeder measurement appears to contribute the most significant portion of theoretical error to the total percent error. However, it was determined by the total error calculations in the mass balance program, that the mass measurement of the settling tank contents contributes the greatest amount of error in kilograms with a value of approximately 1.5 kg. This bench scale system is extremely accurate, however its accuracy is dependant on the full capacity of the scale. Therefore, this error cannot be reduced unless a more accurate scale is put into place. In conclusion the overall error of the mass balance calculation cannot be significantly reduced.

During the time of this research, the TCPDU was undergoing extensive repairs. To test the functionality of the mass balance program, a cold simulation run was performed. The process was simulated by feeding corn fiber into the system, and instead of reacting it, collected it in a vessel. Then the corn fiber was manually distributed to the three scale systems simulating the collection of the accumulation mass in the settling tank and the

outlet masses of char and aqueous waste. Cold nitrogen was also fed through the system to simulate the gas flow in and out of the system. The trial appeared to be successful, with only a few minor bugs that have been corrected. Figure 6 shows the visual representation of the mass balance generated from the simulation run. The solid line represents the sum of the masses and the dashed lines represent the error limits. The mean of the mass balance trend lies within the error limits, indicating that the mass balance is validated.

The capabilities of the mass balance program are quite limited at this time. Several ideas have already been bounced around to improve the usefulness and functionality of this program. This program will continue to evolve and its functionality will gradually increase as new ideas are brought about to improve the mass balance process.

Acknowledgements

I would like to take this opportunity to thank the US Department of Energy's Office of Science and National Renewable Energy Laboratory for giving me the opportunity to participate in this incredible program. Thanks to Steve Phillips for being an awesome mentor and friend and also for his constant guidance, invaluable insight and assistance with this project. I would also like to thank Calvin Feik, who I also consider a mentor and friend, and who has been incredibly helpful with this project. Lastly, but certainly not least, I would like to offer a special thanks to Linda Lung, Patrisia Navarro and the Education Department for their dedication and hard work in coordinating this program.

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Walkenbach, John (1999). Microsoft Excel 2000 Power Programming with VBA. IDG Books Worldwide, New York, NY.

Figures

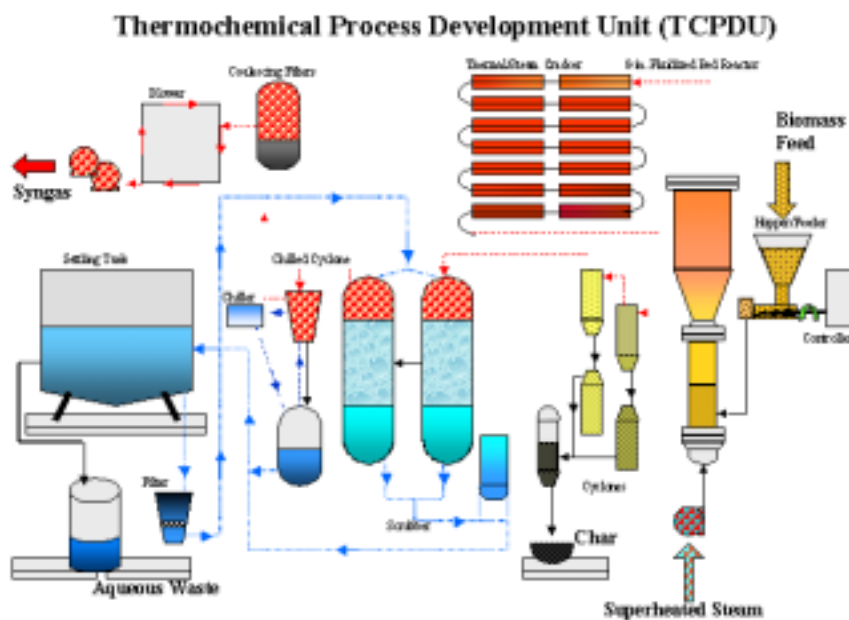


Figure 1. Schematic of Thermochemical Process Development Unit at National Renewable Energy Laboratory in Golden, CO. *NOTE: Schematic should be viewed from right to left.

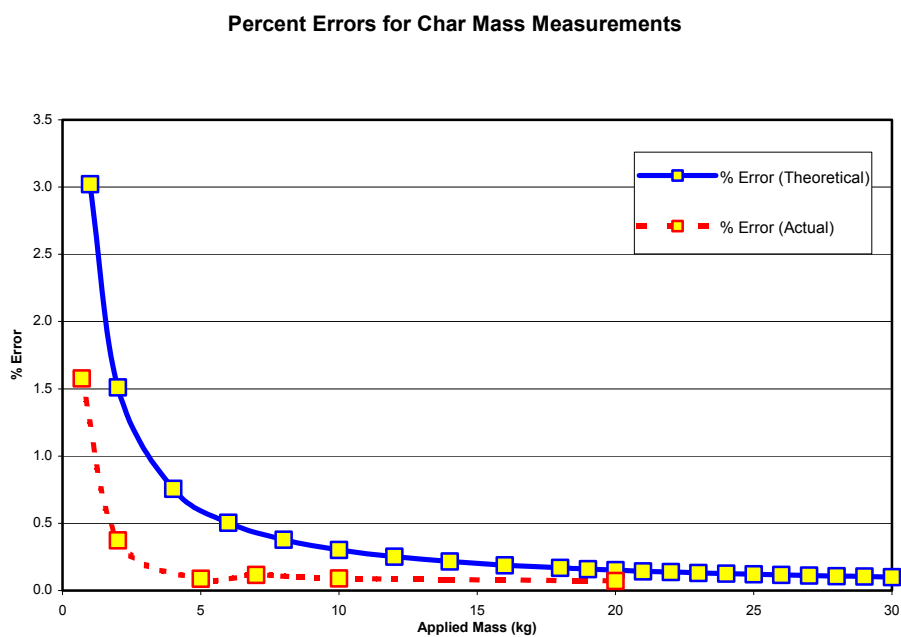


Figure 2A. Correlation of percent error as a function of applied mass for char weight measurements using a bench scale system with a Mettler-Toledo KCC150 bench scale.

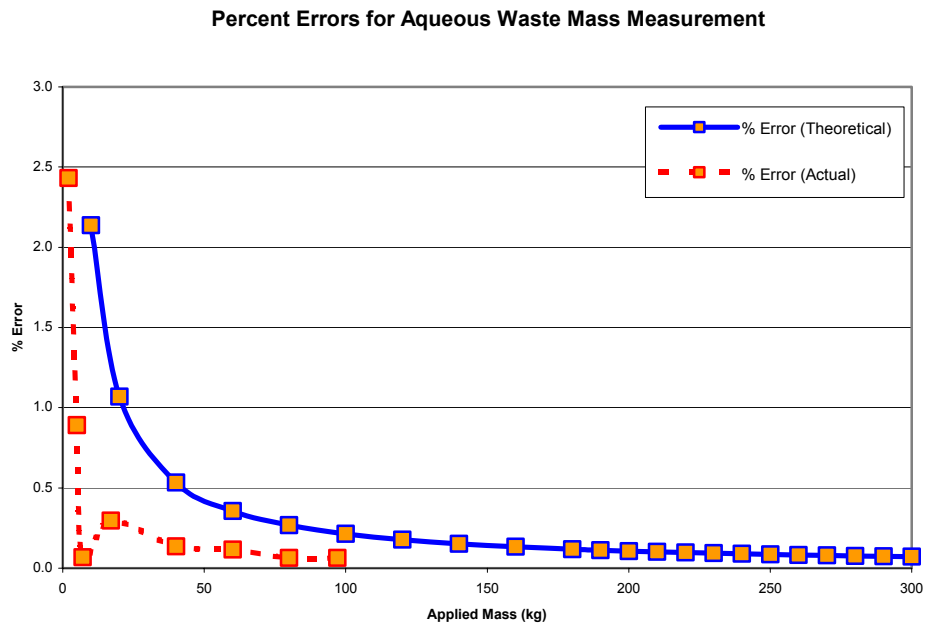


Figure 2B. Correlation of percent error as a function of applied mass for aqueous waste measurements using a bench scale system that consists of two Mettler-Toledo KCC150 bench scales.

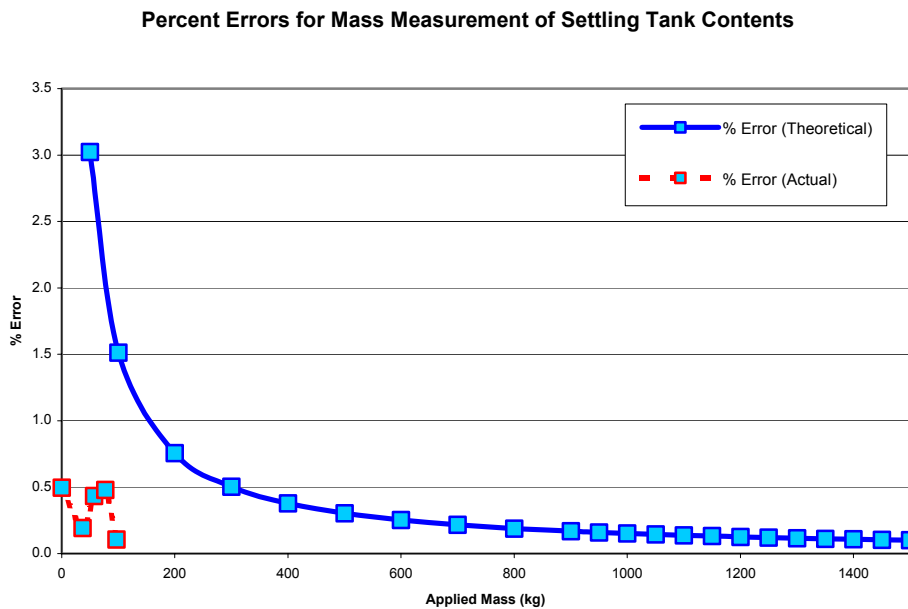


Figure 2C. Correlation of percent error as a function of applied mass for mass measurements of the settling tank contents using a bench scale system with a Mettler-Toldedo KD1500 bench scale.

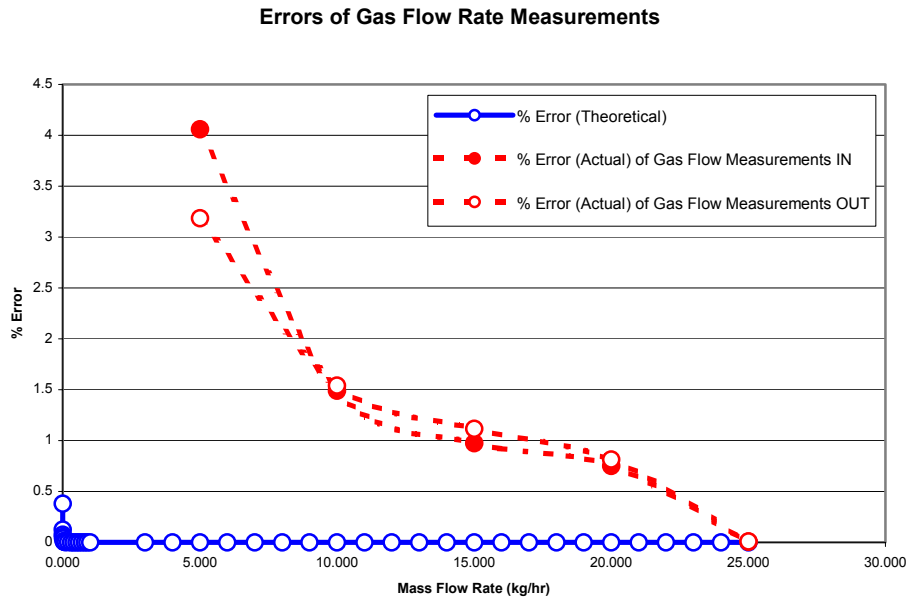


Figure 3. Correlation of percent error as a function of gas flow rate using Micro Motion Coriolis flow meters.

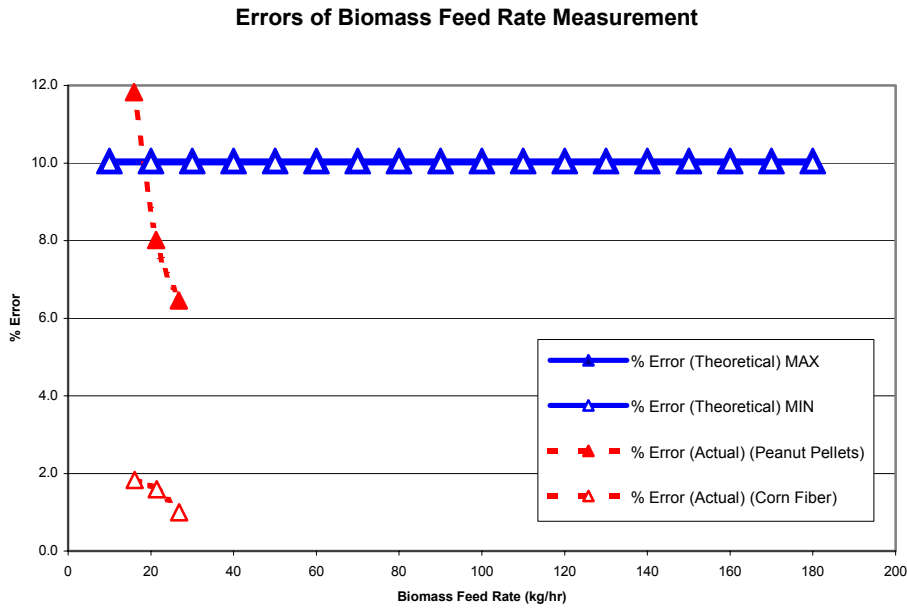


Figure 4. Correlation of percent error as a function of feed rate for solid feed rate measurement using a K-Tron feeder system.

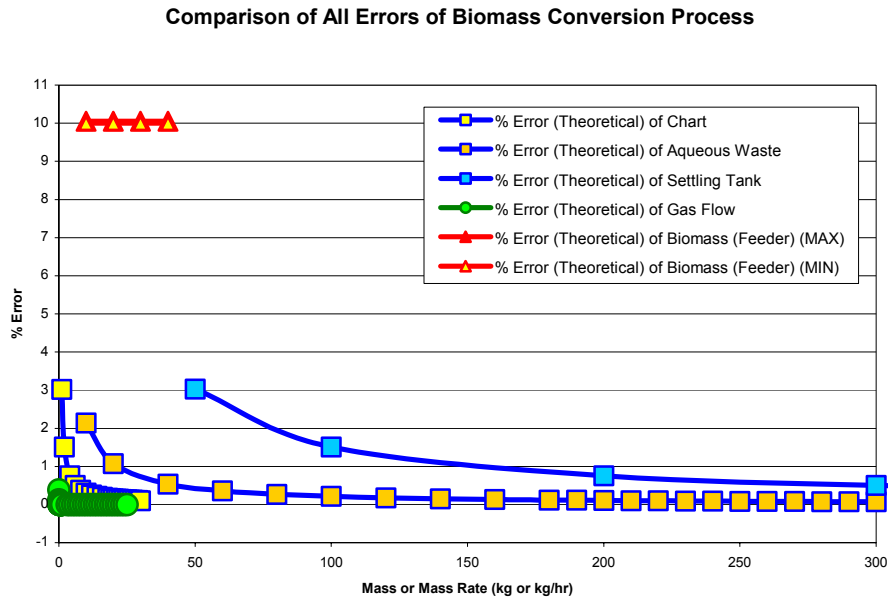


Figure 5. Comparison of all the theoretical errors associated with calculating the mass balance. Percent Error is a function of either mass (kg) or mass flow rate (kg/hr).

Tables

Tables 1A to 1C. Abridged manufacturer's specifications for Micro Motion instruments.

Table 1A. Specifications for Elite Sensor, Model CMF025

Micro Motion Elite Sensor, Model CMF025	
<u>Gas Flow</u>	
Nominal Flow Range	0 to 1090 kg/hr
Maximum Flow Rate	2180 kg/hr
Mass Flow Accuracy	$\pm 0.10\% \pm [(Zero\ Stability/Flow\ Rate)*100\%]$ of rate
Mass Flow Repeatability	$\pm 0.05\% \pm [1/2(Zero\ Stability/Flow\ Rate)*100\%]$ of rate
Zero Stability	0.027kg/hr

Table 1B. Specifications for Field-Mount Transmitter, Model RFT9739

Micro Motion Field-Mount Transmitter, Model RFT9739	
<u>Mass Flow (Gas)</u>	
Accuracy	$\pm 0.10\% \pm [(Zero\ Stability/Flow\ Rate)*100\%]$ of rate
Repeatability	$\pm 0.50\% \pm [(Zero\ Stability/Flow\ Rate)*100\%]$ of rate

Table 1C. Specifications for Field-Mount Transmitter, Model IFT9701

Micro Motion Field-Mount Transmitter, Model IFT9701	
<u>Mass Flow (Gas)</u>	
Accuracy	$\pm 0.10\% \pm [(Zero\ Stability/Flow\ Rate)*100\%]$ of rate
Repeatability	$\pm 0.50\% \pm [(Zero\ Stability/Flow\ Rate)*100\%]$ of rate

For complete manufacturer's specifications, please contact Micro Motion at:

Micro Motion, Inc.

A Division of Emerson Process Management

7070 Winchester Circle

Boulder, Colorado 80301

1-800-522-MASS

<http://www.emersonprocess.com/micromotion>

Tables 2A to 2C. Abridged manufacturer's specifications for K-Tron instruments.

Table 2A. Specifications for Load Cell, Model K-SFT II

K-Tron Load Cell, Model K-SFT II	
Load Ranges	2,000 / 3,000 / 5,000 / 10,000 N
Combined Error	$< \pm 0.03\%$
Repeatability	$\leq 0.001\%$ (Standard deviation of 30 measurements; Measuring time 2 s.)

Table 2B. Specifications for Loss-in-Weight Feeder, Model K-MLT50

K-Tron Loss-in-Weight Feeder, Model K-MLT50	
Feeder Repeatability	$\pm 0.25\%$ -1% of sample average (depending on material characteristics) as 2 Sigma based on thirty consecutive samples taken over one minute, thirty screw revolutions, or 1% of the net supply of hopper capacity, whichever is greater.
Feeder Linearity	$\pm 0.25\%$ of set rate based on ten consecutive samples taken over one minute, thirty screw revolutions or 1% of net supply hopper capacity, whichever is greater over a range from 20:1 full scale.
Batcher Precision	$\pm 0.1\%$ to 1% of batch size depending on material characteristics and cycle time selected.

Table 2C. Specifications for Controller, Model K10S

K-Tron Controller, Model K10S	
Mass Flow Error Limit.	$\pm 10\%$

For complete manufacturer's specifications, please contact K-Tron at:

K-Tron International, Inc.

Routes 55 & 553

Pitman, NJ 08071

(856) 589-0500

<http://www.ktron.com>

Tables 3A to 3D. Abridged specifications for Mettler-Toledo instruments.

Table 3A. Specifications for Bench Scale, Model KDD150

Mettler-Toledo Bench Scale, Model KCC150	
Capacity	150 kg
Readability	1 g (0.001 kg)
Reproducibility (Std. Dev.)	$\pm 0.5 \text{ g (} 5\text{E}^{-4} \text{ kg)}$

Table 3B. Specifications for Bench Scale, Model KD1500

Mettler-Toledo Bench Scale, Model KD1500	
Capacity	1500 kg
Readability	20 g (0.02 kg)
Reproducibility (Std. Dev.)	$\pm 50 \text{ g (} 5\text{E}^{-2} \text{ kg)}$

Table 3C. Specifications for Weighing Terminal, Model ID1 Plus

Mettler-Toledo Weighing Terminal, Model ID1 Plus	
<u>A/D Converter</u>	
Max. Resolution,	7500 e
Verifiable	75000 d
Max. Resolution, Actual	1.17 $\mu\text{V/e}$

Table 3D. Specifications for Analog Output Module, Model 9325

Mettler-Toledo Analog Output Module, Model 9325	
Output Resolution	1 part in 10,000 for either gross or net weight. Accuracy is 0.1% or full scale.

For complete manufacturer's specifications, please contact Mettler-Toledo at:

Mettler-Toledo, Inc.
 1900 Polaris Parkway
 Columbus, Ohio 43240
 1-800-523-5123
<http://www.mt.com/home/countries/usa>